8. Conclusions

The angular distribution parameter measures how well a perturbative treatment of charmonium and the constituent antiproton and proton works. If charmonium could be completely treated perturbatively and the energy scale is high enough, then this parameter would be one. We have determined the angular distribution parameter to be in accordance with the world average for the Ψ, and both the Ψ and Ψ' are produced via the helicity one channel over 75% of the time.

Some care must be taken with the result obtained for the Ψ', since it should not be possible to have an angular distribution parameter greater than one: Otherwise the probabilities C_1 and C_0 are no longer normalized to unity. Both results would have improved with better statistics and a better clusterizer for the central calorimeter, but they both are in agreement within the error bars for previous experimental results and present theoretical predictions.

There are a few reasons why the angular distribution parameter is not one in the charmonium system, especially for the J/Ψ. Principally this is due to the energy at which charmonium is produced. The production process indeed probes distances in the confinement region of the interquark potential between the valence quarks of the proton and between the charm and anticharm quarks. When the interquark distance is smaller, a pure perturbative treatment is more appropriate.

The theoretical derivation of the angular distribution parameter is far from complete. Higher-order Feynman diagrams can still be included, and it is unclear whether one may model the distribution amplitudes in the same way at charmonium energies than at top quark energies. One may also argue about the charmonium potential used in the derivation and the appearance of multi-quark Fock states in the proton. Nevertheless, recent theoretical predictions are quite consistent with experimental results.

Figure 8.1 compares the angular distribution parameter derived in this thesis respectively with previous theoretical expectations for the J/Ψ shown in Chapter 5. The value of 0.53 +/- 0.25 is consistent with most of the theoretical predictions, but it appears that the prediction of Brodsky and Lepage agrees statistically within 2 σ : Charmonium is not a pure perturbative system at the J/Ψ and the quarks involved cannot be treated as massless. Improved statistics is required to favor one of the predictions below α_p=0.8.

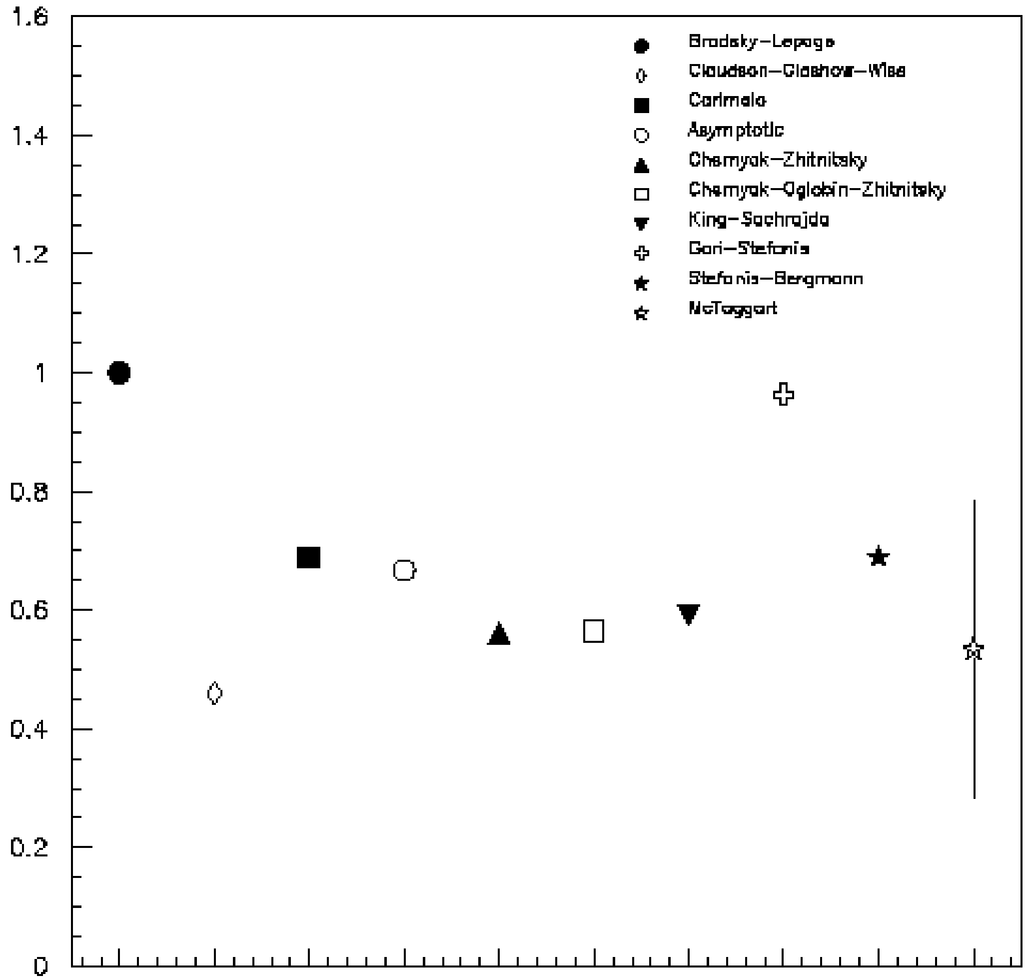

Figure 8.1: Comparison of thesis value with the theoretical predictions for the angular distribution parameter at the J/Ψ.

Figure 8.2 likewise compares the thesis value for the Ψ' with the various theoretical models. In this case, the thesis value prefers the prediction by Brodsky and Lepage for the Ψ'. Furthermore, the value predicted by Claudson, Glashow, and Wise is excluded by the given error.

Significantly, the "heterotic" solution by Stefanis and Bergmann, which offers the best similarity to the world average for the angular distribution parameter and the total width of the J/Ψ to $\bar{p}\,p$, is not excluded by the thesis value at either the J/Ψ or the Ψ'. Only the predictions by Brodsky-Lepage, Claudson-Glashow-Wise, and Gari-Stefanis do not satisfy both thesis values within the experimental errors.

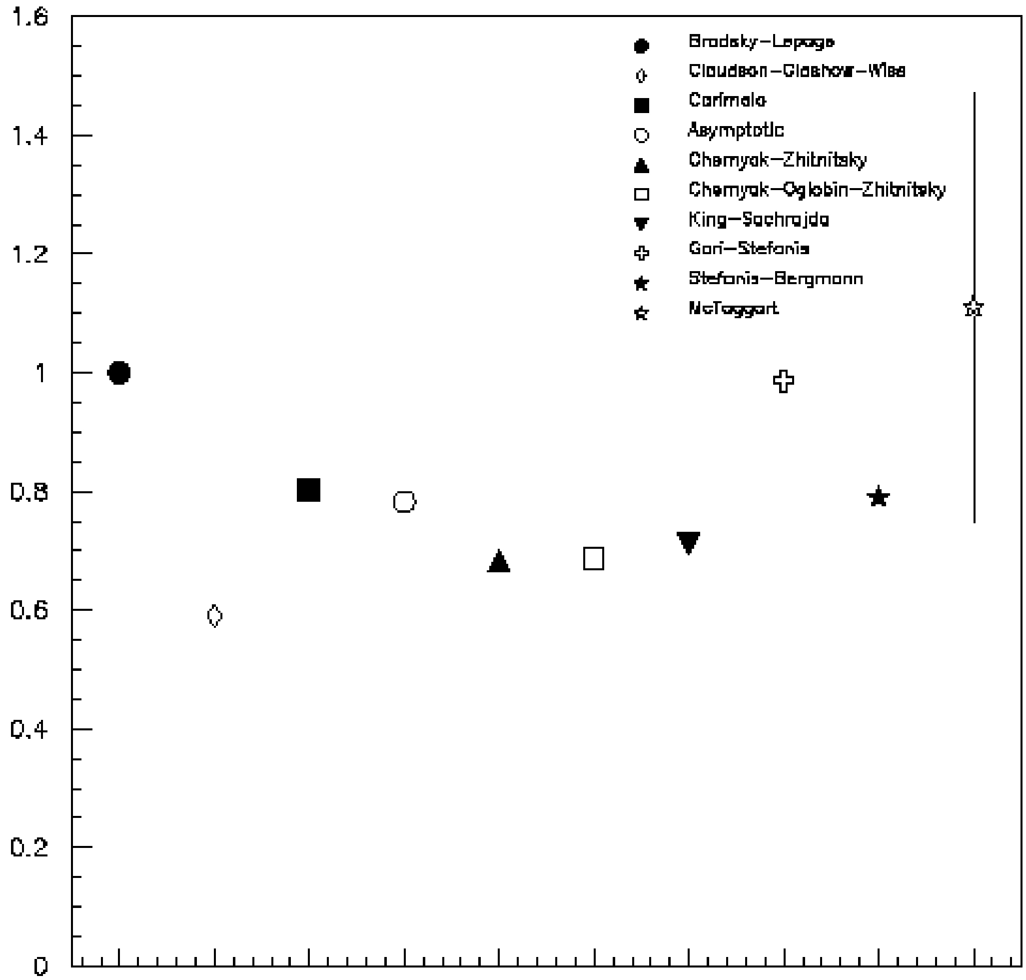

Figure 8.2 : Comparison of thesis value with the theoretical predictions for the angular distribution parameter at the Ψ'.

In Figure 8.3 one may contrast the thesis value for the J/Ψ with previous experiments. The thesis value of 0.53 +/- 0.25 agrees with both the world average of 0.63 +/- 0.08 and lies within the errors of all the previous experiments except Mark I. The proton-antiproton annihilation method (from e760 and e835) is consistent with the electron-positron manner of charmonium production. From the difference between the world average of the angular distribution parameter for the J/Ψ and the thesis value, we quote a systematic error of .10 in the value of α at the J/Ψ and at the Ψ'.

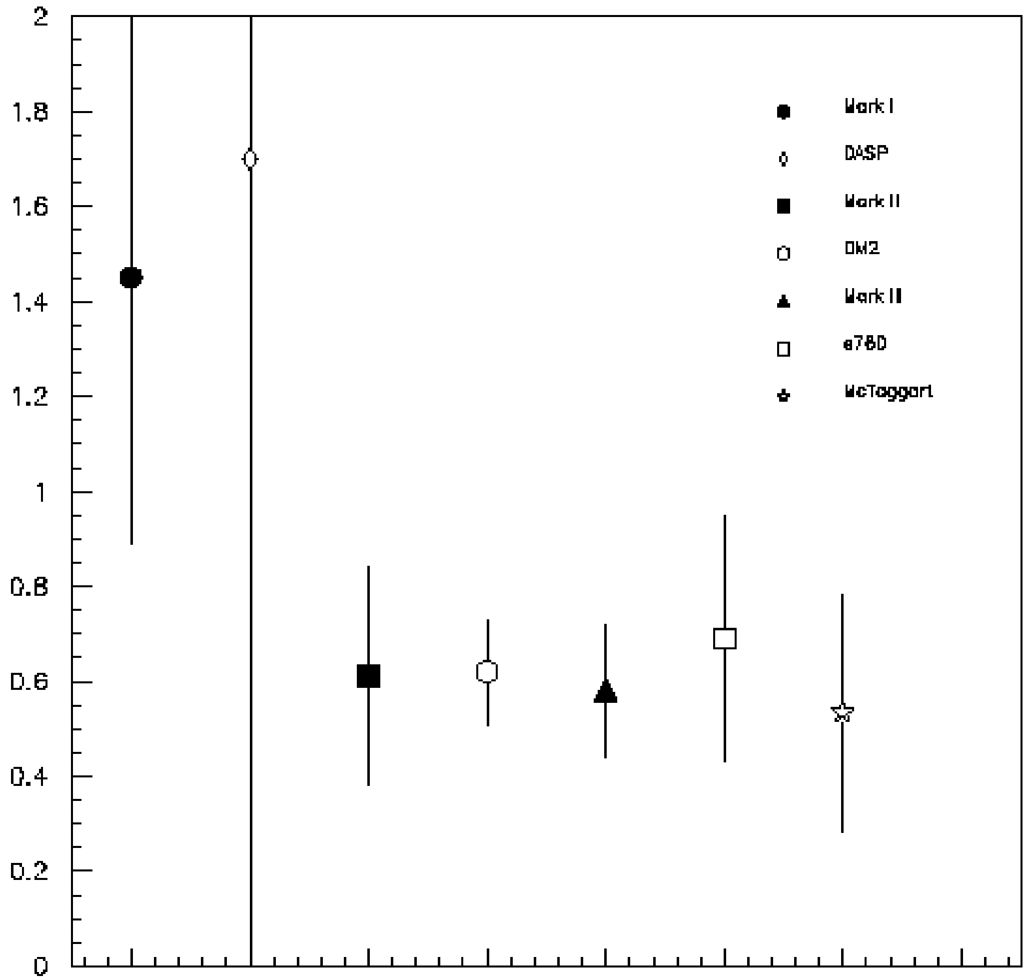

Figure 8.3 : Comparison of thesis value with previous experimental data for the angular distribution parameter at the J/Ψ.

In conclusion, the experimental values presented in this thesis for the angular distribution parameter are consistent within errors with most of the theoretical models and with the current world experimental average. However , the theoretical extremes of a pure perturbative system or of a system where spin-flip amplitudes are negligible are not consistent with results at both the J/Ψ and the Ψ'. Hence spin dynamics and the confinement term in the QCD potential have an effect.

Increased statistics and a value for the width to $\bar{p}\,p$ would help to favor one particular theory, but it appears that the treatment by Stefanis and Bergmann matches both the current world average for the angular distribution parameter and said width the best. In addition, their predictions are not excluded by this thesis. In this instance, non-perturbative effects in the formation of the proton (or dissolution thereof) represented by the quark distribution amplitudes become important.

The final values of the angular distribution parameter derived in this thesis for the exclusive decays of J/Ψ and Ψ' into e+e- from proton-antiproton annihilation are:

$$\alpha_p(J/\Psi) = 0.53 \pm .10(\text{systematic}) \pm .25(\text{statistical})$$
$$\alpha_p(\Psi') = 1.11 \pm .10(\text{systematic}) \pm .36(\text{statistical}).$$